PKE-Nefedov: The first basic science experiment on the International Space Station

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The Plasma Crystal Experiment, PKE-Nefedov, is the first basic science experiment on board of the International Space Station ISS. It will cover a long-term investigation over about one year on complex plasmas under microgravity conditions.

The experimental setup is a symmetric parallel plate rf-discharge working in a push-pull mode for the rf-excitation. The rf-generator is a special development which allows to go down to very low rf-power values, which are necessary for the plasma crystal formation. The feeding gas is Argon and a vacuum connection to space is used to pump down and control the pressure in the experimental chamber. Two different monodisperse particle sizes can be injected into the plasma between the two electrodes – 3.4 µm and 6.9 µm in diameter – as well as a mixture of both sizes.

The first set of experiments, the so-called “basic experiments”, performed in the beginning of March by the first permanent crew on the ISS were dedicated to investigate the complex plasma over a broad range of parameters. Each particle size and the mixture was investigated at different Argon pressures and rf-powers in one basic experiment lasting 90 minutes of total experimental time. The neutral gas pressure was adjusted between 0.1 and 1.0 mbar in five steps. At each pressure we used five rf-power (forward) steps below 0.3 W. The motion of the particles in low and high resolution were recorded on two VCR’s during these experimental runs allowing us to investigate the complex plasma under microgravity conditions in great detail.

We expect interesting new insights into the complex plasma under microgravity conditions from the basic experiments. About 10% of the video data were directly transmitted during the experimental runs. >From these we got the information about the proper function of the complex apparatus and got the first interesting scientific data about the behaviour of complex plasmas under microgravity conditions. The whole set of data will be available in the beginning of April. In this talk we will present the first results from this mission.

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DUSTY STRUCTURES IN CRYOGENIC PLASMA

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Dusty structures of magnesium oxide particles of 5 - 20 microns in diameter were observed experimentally in the dc glow and capacitive electrodeless RF discharges at the temperature of fluid nitrogen (77 K). The 13.6 MHz RF discharge was lit up in the air between two copper foil rings stringed on the quartz tube 2 cm in diameter at the distance of 4 cm apart. The volumetric localization of dusty particles in the capacitive RF discharge of low pressure with given electrodes configuration was not explored earlier. Such RF discharge is controlled completely by ambipolar diffusion. The plasma localized between rings serves as electrostatic trap for negatively charged macroparticles.

There is a very dense dusty-plasma structure hanging at the middle between two rings at the fluid nitrogen temperature. The distances between particles in this structure are difficultly distinctive even at good magnification. The structure is about 2 cm length and about 2 mm in diameter. Around this structure the threads of particles were observed. It is well visible at laser illumination along a tube axis that the structure surface do not only intensively diffuses a laser radiation, but also reflects it. Though the mutual arrangement of particles in separate layers did not manage to be observed it was visible that increasing of gas pressure leads to restructuring. At pressure increase the dense structure in the cryogenic RF discharge divides into layers in spite of the fact that the ionization in this area remains homogeneous. The precise dark and light thin transversal stripes with sharp boundaries are visible on whole structure length. The dusty particles are absents in dark stripes. It can be either standing sound waves determined by development of ultrasonic instability in dusty plasma or charged narrow nonlinear dusty layers of the soliton type similar those which are processes of dusty structures.

The formation of very dense dusty structures at cryogenic temperatures may be explained by diminishing of Debye screening radius which is determined by ions temperature and essentially weakening of mutual Coulomb repulsion of charged macro particles. In this case the dusty particles can approach closer to each other and there attraction determined by mutual polarization of ionic clouds surrounding this particles becomes more essential. This is the interaction of a charge-dipole or induced dipole type. Though its short-range it can be enough strong for the distances comparable to the ionic cloud size. At low temperatures in very dense observed structures the dust particles shades each other so strongly that the free path of ions becomes less than the structure size. Under these conditions the attraction of dusty particles is possible by only of the electrostatic forces. Under experimental conditions at gas temperature $T=77^0K$, ion concentration was about 10^9 cm^{-3}, and Debye radius was about 20 microns. The dust concentration in dense structure can be estimated basing on electro neutrality requirement. At microparticle charge $q \sim 10^3$ the particle density n_d in structure cannot exceed 10^6 cm^{-3}. In this case the ion path length in a charged dust is about 0.01 cm. Nonideality parameter is about 10^4.

Thus, it was possible to receive super dense ordered dusty-plasma structures at cryogenic temperatures in the RF low-pressure discharge, which were not observed earlier in usual conditions. The instabilities leads to structure division into thin transversal layers with precise boundaries and it may be observed when gas pressure decreases.

Normal Modes of 2D Coulomb Clusters in Complex Plasmas

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Complex plasmas consist of small solid particles immersed in a gaseous plasma environment. Usually, the particles are spherical and of micrometer size. The particles attain high negative charges of the order of several thousand elementary charges due to the inflow of plasma electrons and ions. In typical experiments, the particles are trapped in the sheath region of an rf discharge where the electric field force levitates the particles against gravity.

A small number of particles ($N = 1$ to 100) can be trapped in a single layer in the vertical direction, forming a 2D system. In the horizontal plane, the arrangement of the particles is determined by the interplay of interparticle Coulomb forces and the horizontal confinement. From simulations [1, 2] it is found that the particles arrange in concentric shell structures with "magic" numbers, known as Coulomb clusters or "artificial atoms". Finite clusters have been observed in recent experiments [3, 4].

Finite Coulomb clusters have a number of normal modes [1]. One mode is the intershell rotation, where two or more concentric shells of the clusters rotate with respect to each other. This mode has previously been investigated experimentally and compared to simulations [4]. Normal modes in 1D arrangements have already been identified from probe-wire stimulated oscillations [5].

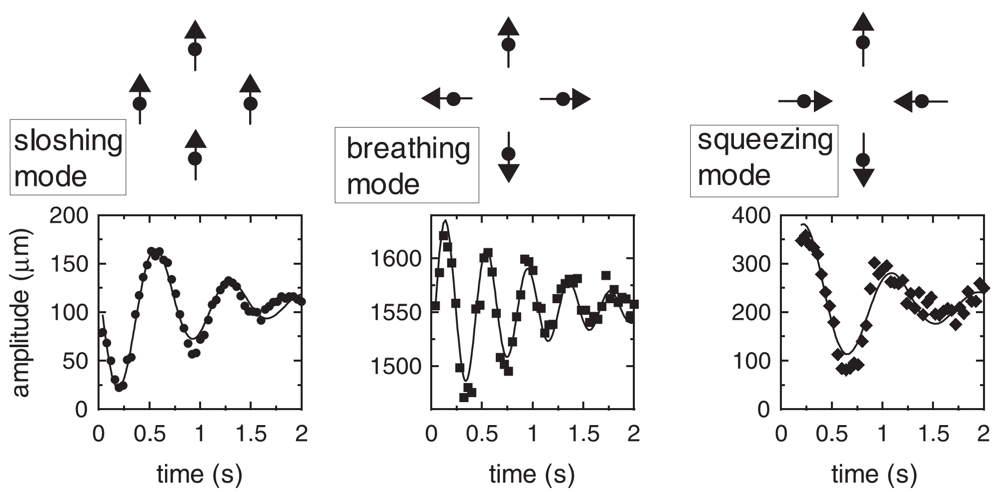

Abbildung 1: *Normal modes of a $N = 4$ finite cluster.*

Here, we present experiments on a number of other modes, like the "sloshing" mode, the "breathing" mode and the "squeezing" mode, which are depicted in Fig. 1 for a cluster of 4 particles. The modes are excited by a pulse-shaped disturbance of the plasma environment which causes the cluster to oscillate with a superposition of several modes. Different modes have been identified. From the measurement of the frequency of the different modes, the crucial parameters of a complex plasma like particle charge Q and the screening strength κ of the interparticle potential are determined independently.

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Defects Mediated Particle Motions of Strongly Coupled Dust Coulomb Clusters

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Microscopic particle motions influenced by the intrinsic and thermal defects (ID and TD) in strongly coupled two-dimensional (2D) dust Coulomb clusters with and without external driving forces are investigated both numerically and experimentally. Under the central field confinement, the system has a core with triangular lattice surrounded by outer circular shells with IDs. The regions around IDs are vulnerable to thermal agitation. Increasing temperature causes the formations of TD clusters associated with particle motions from IDs. In the liquid state, the screening of IDs by TDs washes out the boundary effect. Introducing a narrow laser beam through the cluster center generates particle motions through the radiation pressure. For the crystal state, a supercritical transition to the disordered state is observed with the increasing stress. Particles first collectively move along the lattice line toward one of the six IDs when the external stress reaches a threshold. The motion also initiates defect rearrangements. For the liquid state, in addition to TDs, extra defects are further generated by the external stress associated with the chaotic vortex type excitations initiated from the driving zone. Nonlinear transports are enhanced.

Is There a Frequency Gap in the Spectrum of a Dusty Plasma Bilayer?

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A bilayer of charged particles (that consists of two quasi two-dimensional layers separated by a distance *d*) has two collective modes: an in-phase and an out-of-phase oscillation. With simple Coulomb interaction the mode spectrum is well understood[1]: correlations have an important effect on the behavior of the out-of-phase mode. When the two layers are weakly coupled, the out-of-phase mode exhibits an acoustic behavior, but strong coupling induces a frequency gap, *i. e.* changes the *acoustic* to an *optic* behavior. The frequency gap is a sensitive function of the layer separation *d* and of the coupling strength Γ.

The same qualitative behavior prevails when the interaction of the particles is a screened Yukawa interaction, although obviously the magnitude of the frequency gap also depends on the screening parameter κ. The calculation requires the input of the interlayer pair correlation function. We have estimated the expected frequency gap by using an HNC generated Coulombic correlation function (which at least for small κ is not substantially different from the exact Yukawa correlation function[2]) and show its behavior for a range of expected dusty plasma parameters.

The more interesting question is how the attractive interlayer interaction affects the formation of the frequency gap. Qualitative arguments indicate that the frequency gap survives, but its dependence on the layer separation will be affected. A reasonably good insight is provided by looking at the Coulombic bilayer case, where the two layers consists of oppositely charged particles[3].

Measuring the dispersion of the out-of-phase mode both under laboratory and microgravity conditions would provide an excellent opportunity to test the difference between the interlayer interactions in the two situations.

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Thermally excited waves in a 2D plasma crystal

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Thermally excited longitudinal and transverse waves were experimentally detected in a two-dimensional (2D) plasma crystal. We found that these self-excited waves exist over the whole range of dispersion relations. In addition, we verified the existence of negative dispersion, i.e., backward wave characteristics, for the longitudinal mode at a large wavenumber: $ka/\pi > 1$. The dispersion relations for both modes agree the theory of Wang et al.[1], and they also agree with our experimentally-measured dispersion relations using laser excitation of the waves.

Experiments were carried out using a parallel-plate radio-frequency discharge. Polymer microspheres were shaken into the plasma, where they were levitated by the electric field in the sheath above the lower electrode. The particles arranged in a single horizontal layer, with a hexagonal lattice. They were imaged using a video camera, which recorded the particle motion. The motion of the particles was analyzed to obtain dispersion relations of thermally excited waves.

An example of 2D spectrum in ω and k space for thermally excited waves is shown in Fig. 1. The results indicate that thermally excited wave for both modes exist over the entire possible range of k, and their amplitude was mostly the same, regardless of k.

For the longitudinal mode, strong "dispersion" characteristics, i.e., curvature of a dispersion relation, was observed. The backward wave characteristics is also seen at a large k. In contrast, the transverse mode exhibited a linear relationship of ω vs k, *i.e.*, "dispersionless" characteristic over a entire range of k ($0 < ka/\pi < 2$)[2].

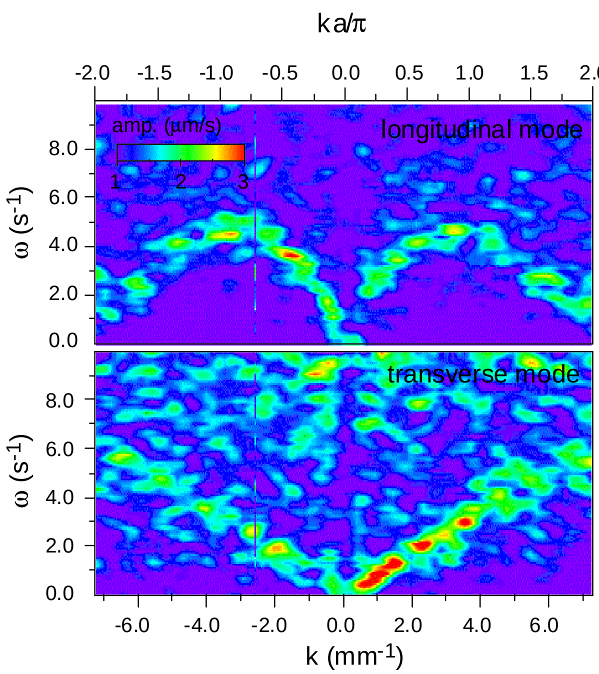

Fig. 1. Dispersion relations of thermally excited waves. Experimental data are shown for the full range of the wavenumber in a triangular lattice, for propagation parallel to the lattice's primitive translation vector.

The sound speed C_l of the longitudinal mode is faster than C_t of transverse modes. In our experiments, the sound speed is a few cm/s for longitudinal mode and several mm/s for transverse mode, respectively. Therefore, the ratio of C_l / C_t is approximately 5 for $\kappa \sim 1$. The wave frequency and wavelength are typically a few Hz and several mm, respectively, for both modes.

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Equation of state for complex plasmas

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Complex (dusty) plasma experiments in low-density gas discharges clearly show the existence of crystalline, liquid, and gaseous states. This has precipitated experimental and theoretical studies of phase transitions in the plasma. But so far, there is no relatively simple analytical model that describes the equation of state (EOS) for complex plasmas over a sufficiently wide range of parameters.

We have conducted experiments to directly measure the EOS for complex plasmas. A large ensemble of monodisperse particles was embedded in a rf plasma and confined in a "squared" potential well formed inside a glass cylinder. Increasing gradually the pressure p on the particles and measuring the particle kinetic temperature T we get the empirical EOS p=p(n,T) for a given particle density n. Using these data, we retrieve the first virial coefficient and thus construct a Van der Waals'-like analytical equation which can describe the EOS in wide range of parameters. We also discuss deviations of the empirical EOS from that of an ideal gas and draw conclusions about short- and long-range parts of pair interparticle potential.

Transport Characteristics of Particles in Dusty Plasma in Microgravity under Solar Radiation

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The results of the experimental studies of the diffusion of dust, charged by a photoemission in microgravity conditions are presented. The data were obtained during investigations of dusty plasma induced by solar radiation (space station "Mir"), which shown that under action of intensive solar radiation the micron-size particles may acquire the considerable positive electric charges [1]. The experimental study of dust diffusion were performed for bronze particles with the mean radii $a \cong 37.5$ μm in background gas (neon) at the pressure $P \cong 40$ Tor. The particles were contained in a cylindrical glass ampoule, the bottom of which was the uviol window intended for the solar irradiating of dust cloud. Extra irradiating of particles by a laser beam was used for an improved diagnostics.

The complex measurements of velocity distributions, temperatures, friction coefficient and diffusion constants of macroparticles in dusty plasma were carried out. The dust system under study represented a weakly correlated fluid with $\Gamma \sim 40$, and the value of interparticle interaction in which practically did not influence on the processes of mass transport. The comparison of experimental data and theoretical estimates has shown, that the dynamic behavior of macroparticles for $t < 10$-15 s was determined by process of the ambipolar diffusion. It should be noted that any observations of ambipolar diffusion for charged macroparticles are not feasible in usual laboratory conditions at presence of force of gravity of the Earth.

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Waves in Collisional Dusty Plasmas

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Dusty plasmas, or ionized gases containing charged dust of micron to sub-micron size, occur in a variety of space and laboratory environments. The presence of charged dust in a plasma modifies the propagation and stability properties of standard ion waves and leads to the appearance of new low frequency dust waves and instabilities. We summarize some recent work on several instabilities in collisional dusty plasmas, with applications to dusty plasmas in the Earth's lower ionosphere and in laboratory experiments where neutral densities are relatively high. This includes Hall current instabilities in both the ion and dust frequency ranges, a resistive ion-dust two stream instability, and a drift instability. Applications to dusty plasmas in the lower ionosphere (e.g., dusty meteor trails, polar mesospheric clouds) and to laboratory wave experiments are discussed. We also consider aspects of the interaction of electromagnetic waves with waves or structures in collisional dusty plasmas.

Effects of dust particles on electrostatic waves in magnetized plasmas

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Electrostatic waves of dusty plasmas in a uniform magnetic field are studied. Unless the magnetic field is extremely strong, the dust particles can hardly be magnetized, while however, electrons and ions are easily done so. Electrostatic modes in such dusty plasmas can then be investigated making use of non-magnetization assumption for dust particles.

In the high frequency range, due to the existence of dust component, both frequencies of Langmuir waves (parallel to the magnetic field) and upper hybrid waves (perpendicular to the field) are reduced. In the frequency range of ion waves, besides the effect on dust-ion-acoustic waves propagating parallel to the magnetic field, the frequency of ion cyclotron waves perpendicular to the magnetic field is also enhanced. As the dust particle density increases, the mode becomes more acoustic-like than cyclotron-like. The other effect is that the low hybrid mode is affected in the same way as the dust-ion-acoustic mode. In the very low frequency range, we find an "ion-cyclotron-dust-acoustic" mode propagating across the field line with a frequency even slower than dust acoustic waves. Corresponding experiment is also proposed.

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Solitons in a 2D strongly coupled complex (dusty) plasma.

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Solitary waves were studied in a 2D strongly coupled dusty plasma. The experiments were performed in an rf parallel plate discharge [1]. A monolayer dust lattice was formed from monodisperse plastic microspheres and levitated in the electrode sheath. Linear compressional pulse waves were launched in the lattice. The wave structures were directly imaged with a high speed video camera and analyzed with particle tracking software. It was found that the pulses propagated with no or little change of the shape, thus resembling solitons.

The theory describing the experiment is based on a set of equations of motion written for a monolayer hexagonal lattice. It takes into account damping, dispersion and nonlinearity. The resulting KdV equation allows determination of the relation between the particle charge and the screening length of the lattice in the Yukawa approximation.

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KdV-ZK solitons in multispecies dusty plasmas

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Korteweg-de Vries-Zakharov-Kuznetsov (KdV-ZK) equations have been derived for quite a number of different electrostatic modes in plasmas that propagate obliquely to a static magnetic field. The simplest model is that of ion-acoustic solitons, where the hot isothermal electrons are described by a Boltzmann distribution, while the cooler ions are treated as a fluid with adiabatic pressures. Many variations on that basic theme occur in the literature. One is where different positive and negative ions are present, so that a large enough concentration of negative ions can alter the character of the solitons from compressive to rarefactive. The transition occurs at critical densities, for which the KdV-ZK equation is no longer the appropriate nonlinear paradigm, but one finds the modified KdV-ZK (mKdV-ZK) equation, with cubic rather than quadratic nonlinearities. Another possibility is to consider two distinct electron species, one hot and isothermal, the other cooler and adiabatic, which together with magnetized or unmagnetized ions leads to electron-acoustic solitons.

More recently, attention has turned to dusty plasmas, where one or more charged dust components have introduced space and time scales that differ vastly from those associated with the usual ions and electrons. Here the prime example is the dust-acoustic mode, well studied both in theory and in the laboratory [1]. It is thus of interest to revisit the whole field of electrostatic modes in magnetized plasmas in a general treatment that encompasses all the known dispersion laws and non-linear equations. For this, we will distinguish three classes of species, each of which including initially an unspecified number of constituents. The cooler adiabatic species are described by standard fluid equations, including the one governing the pressure variations. Besides those, we will allow for two extremes: on the hot side, several Boltzmann species can be considered, corresponding effectively to the massless limit where inertial effects vanish because the thermal velocities exceed typical wave and translational speeds. On the sluggish side, several immobile background species are included, to simulate the case of unmagnetized ions (dust) when describing electron-acoustic or dust-ion-acoustic solitons.

Specific results for dusty plasmas include the possibility that dust-ion-acoustic solitons become rarefactive rather than compressive, if enough electrons are depleted onto the charged dust grains. For the lower-frequency regime dust-acoustic solitons are rarefactive when considering negatively charged dust, and compressive in the opposite case. To avoid ambiguities, compressive and rarefactive refer to the behaviour of the electrostatic potential rather than to densities of particular species. There thus emerges a general property of KdV-ZK solitons in plasmas with only one sluggish species, namely that the sign of the charge of the latter determines their compressive or rarefactive nature. Streaming effects between different dust species and/or a combination of negative and positive dust can also change the nature of the KdV-ZK solitons. Very close to the critical densities and beam velocities, the mKdV-ZK solitons are more relevant, showing a typically broader profile than KdV-ZK solitons and allowing for both compressive and rarefactive solutions.

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Ionization Properties of the Dusty Mesosphere

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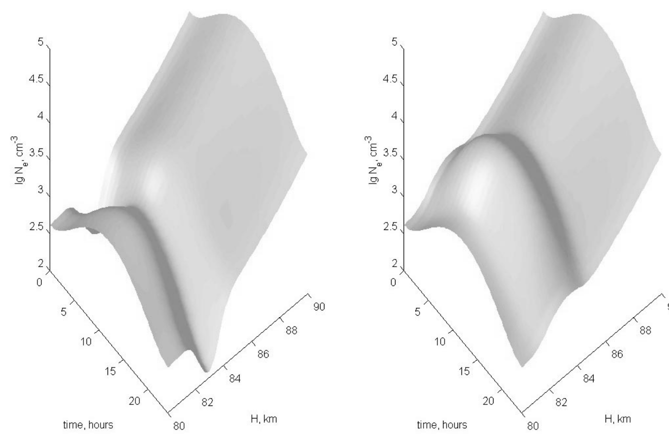
The problem of influence of the dynamics and charging of dust particles on the ionization properties of the polar summer mesosphere is considered. This problem is connected with the problem of explanation of some layered structures in the Earth's upper atmosphere, which are known as noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE). These structures are believed to be associated with the presence of a large amount of charged dust or aerosol in the upper atmosphere. The great interest in these structures is due to their possible connection with Earth's global warming process. We introduce the notion "dusty mesosphere" for the layer of the mesosphere at the altitudes of approximately 80-90 km, where the conditions for the nucleation and formation of macro (dust) particles are fulfilled.

We propose the self-consistent model, which describes and takes into account nucleation of particles, the growth of dust particles in size, dust particle charging process, ionization, recombination, solar radiation, photoelectric effect, sedimentation, as well as self-consistent electric fields. We calculate spectra of solar radiation at the altitudes corresponding to dusty mesosphere and analyze the possibilities of the formation of dust particle structures[1]. The model allows us to explain the most important ionization effects observed in the polar summer mesosphere, in particular, electron and ion depletions as well as the ionization layers. It is shown that these effects are related to the presence of charged dust. Figure presents the typical calculated manifestation of the dusty layer in the mesospheric plasma: the presence of dust can result in both electron depletions (left panel) and electron density increase (right panel). The results reflect an important role of the material of dust. The left panel corresponds to the case of high enough photoelectric workfunction (dust consists of ice), while the right panel fits the case of low workfunction (dust consists of alkaline metal).



We assume to develop the model to describe self-consistently the process of formation of the observed dust structures such as NLC and PMSE.

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Dynamics of Charged Dust in Some Space Environments

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Here I will discuss the dynamics and thermodynamics of charged dust in a few selected space environments. I will begin by reviewing some continuing work (in collaboration with G. Sorasio and M. Rosenberg) on the flight of micrometeoroids encountering the earth's atmosphere. Here the important role of thermionic emission as an additional source of electrons along the meteor path, as well as its role in flipping the grain charge polarity will be discussed. I will next present some preliminary work concerning the charging and dynamics of grains formed in expanding supernova shocks and subsequently injected into the hot interstellar medium. Here secondary electron emission by energetic ($\geq$ 10 kev) streaming ions is the dominant grain charging process, and sputtering is the dominant mass loss process. I will conclude with a few comments on the charging and dynamical evolution of interplanetary grains that form the circum-solar rings (around 4 solar radii) that are seen during some total solar eclipses.

DUSTY PLASMA EFFECTS AT JUPITER & SATURN

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I will report on the ongoing analysis of the Galileo dust/plasma measurements at Jupiter as well as the common observation of the Jovian magnetosphere by Galileo and Cassini. Also, I will show recent modeling results of Saturn's E-ring, the region that will be crossed many times by Cassini in orbit about Saturn.

On the last day of year 2000, Cassini had its closest encounter with Jupiter and made simultaneous measurements with Galileo. The fluxes seen by Cassini were comparable to the fluxes measured by Galileo that was much closer to Io, the putative source of dust. These common observations indicate, that contrary to the original models of dust acceleration in the inner magnetosphere of Jupiter, there must further processes to energize dust particles as they cross the outer parts of the magnetosphere.

Our most recent E-ring model is based on the latest analysis of the Voyager plasma observations. We parameterized the characteristic physical quantities (escape flux from all the E-ring satellites, power index of the escape ejecta; 4 parameters) and used them to fit the 'pole-on' brightness profile based on ground-based observations . We verified that this fit also agrees with the observed brightness distribution.

Charging of dust particles on surfaces

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Experimental investigations have been made of the charge on dust particles resting upon a metal surface in vacuum.[1] The surface is agitated so that the particles drop though a small hole and a Faraday cup beneath measures the charge on each particle. The surfaces are metals (Hf, Zr, V, W, Co, Ni, Pt and stainless steel) and the dust grains are both metallic conductors (Zn, V, and stainless steel) and insulators (silica, alumina, Martian regolith simulant, and lunar dust simulants) in the size range of 35 – 200 microns. The basic charging mechanisms studied are contact charging, electrical induction in presence of an electric field, and charging under UV illumination.

The contact charge is consistent with a model based upon the grain capacitance and the effective contact potential between the grain and surface.[2] Investigations of the charging by contact with different metal surfaces allow the determination of the effective work function of dust samples. An electric field above the surface induces an additional charge on metallic grains consistent with Gauss's law. The relation of the induced charge for spherical dust grains with radius r, $Q = 4\pi\varepsilon_0(1.64)E_0 r^2$, was found to be a good approximation also for irregularly shaped dust grains.[3] The induced charge on insulating grains increased with repeated agitation of the surface. UV irradiation may increase or decrease the charge depending upon the relative importance of photoemission and photoconductivity.

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The Dynamic Mach Cone as a diagnostic method in reactive dusty plasma experiments

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We have extended the Mach Cone diagnostic method for dusty plasmas[1-4] to what we call the Dynamic Mach Cone (DMC)[5] concept when the dust properties such as mass and/or charge may change. In reactive dusty plasma experiments the particle growth rate can be high so that the mass may change substantially during one passage of a body creating a Mach Cone. When the mass increases the dust acoustic wave (DAW) velocity decreases and the DMC shape will be concave. In some coating experiments the dust properties may change and this may lead to charge changes while the mass is relatively unaffected. If the charge increases the DAW velocity will increase and the DMC shape will be convex. We demonstrate the shapes of DMC?s in selected cases.

We also show how the instantaneous observation of a DMC can be used to find the time history of the DAW velocity. This may again lead to knowledge on the growth rates or coating rates of the dust. The DMC therefore have the potential of being a useful method for monitoring and investigating conditions in reactive dusty plasma experiments.

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Mach Cones in Two-Dimensional Yukawa Crystals: Linear and Nonlinear Properties

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Molecular dynamics simulations of compressional and shear Mach cones in a two-dimensional, hexagonal dusty plasma crystals are presented. The initial conditions and physical parameters (such as the dust charge, inter-particle spacing, the Debye length, and externally imposed laser force) are chosen to match experimental conditions. The inter-particle potential is assumed to be Yukawa. In order to determine the test the validity of linear theory, we carry out both the linear and nonlinear simulations. For the conditions of the experiment, it is found that while linear theory provides a qualitatively correct explanation of multiple compressional Mach cones in the far-field region, nonlinear effects play an important role in determining the spatial structure and magnitude of the flow and density perturbations associated with the compressional cones in the near-field region. The separation of the first and second compressional cones is smaller in the nonlinear than in the linear simulations. Furthermore, the magnitude of the density and velocity perturbations seen in the nonlinear simulations is nearly twice as large in the linear simulations. We demonstrate the excitation of shear Mach cones and discuss, in particular, the effects of varying the dust charge or and the laser force.

Shear Wave Mach Cones in a 2D Dusty Plasma Crystal

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Shear wave Mach cones were observed experimentally in a 2D dusty plasma crystal (Fig.1,2). The plasma crystal was formed by 8.69 μm polymer microspheres suspended in a low pressure Ar rf plasma. Mach cones were launched using the laser excitation technique of Melzer *et al.*[1], except that here the laser spot was moved in the direction perpendicular to the momentum imparted to dust particles by laser photons. This variation of the technique avoided perturbing the area in the center of the Mach cone's "V", thereby allowing observation of structures that would otherwise be obscured. The Mach cone angle relation was verified in a wide range of scanning speeds, giving the sound speed of shear waves of 5.8 mm/s. This is consistent with observations of shear wave pulse propagation. Direction of particle motion in the shear wave Mach cones was parallel to the cone wings, which is different from compressional wave Mach cones. As another indication of shear wave origin of the observed Mach cones, we verified that the so-called numerical Schlieren map technique revealed no compression or rarefaction of the lattice associated with the cone.

A rich wake structure was also observed (Fig.2), consisting of multiple lateral and transverse wakes, and compressional wave Mach cones, for scanning speeds exceeding sound speed of compressional waves. This wake structure was predicted by Dubin[2].

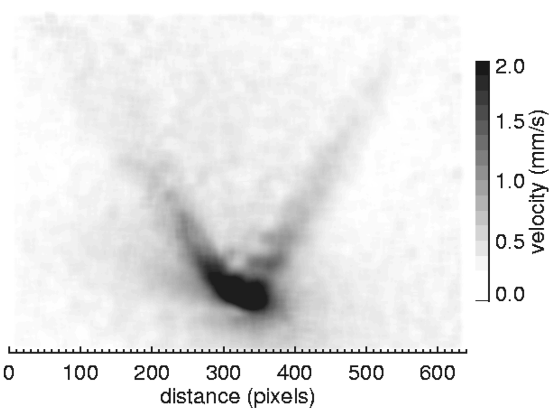

Fig.1. Grey-scale speed map of shear wave Mach cone. ($M_{comp.}$ = 0.5).

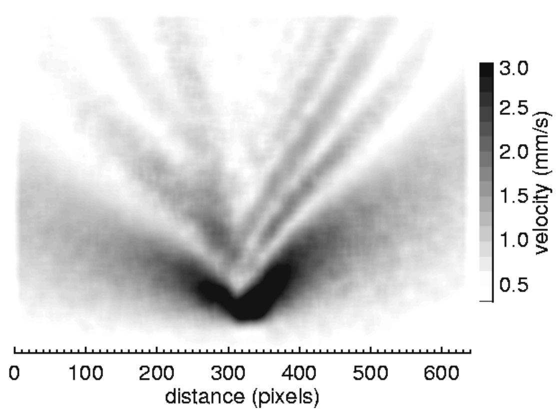

Fig.2. Grey-scale speed map of wake structure, including compresssional and shear wave Mach cones, and multiple lateral wakes. ($M_{comp.}$ = 1.2).

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Spinning of dust particles suspended in an RF sheath

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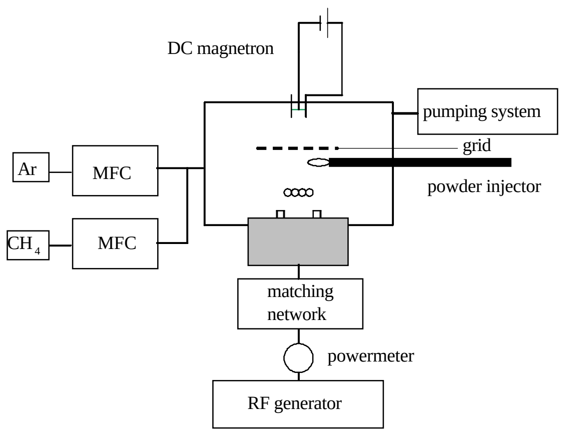

Figure 1: Plasma chamber

In a capacitively coupled RF discharge in argon, dust particles are injected by a modified salt shaker. The bottom electrode, which is RF powered at 13.56 MHz, is mounted in the bottom of the vacuum vessel. On the electrode, a copper ring is positioned in order to improve the trapping of the injected dust particles. In the top of the vacuum chamber, a magnetron can be inserted. This magnetron serves to evaporate copper. The copper vapor can then coat the suspended particles. In the figure below the plasma chamber is depicted schematically. The particles used are 10 micron sized particles of BAM, one of the components of phosphor powders which are used in fluorescent lamps. In the end, the goal is to coat those particles with a material which prevents mercury vapour from entering the particle while remaining transparent for UV light. If the particles have to be coated uniformly, they should not freeze into Coulomb crystals and they should preferable spin around. The particles are expected to be non-spherical.

In order to verify the spinning, the magnetron is replaced by a window and the particle cloud is illuminated from the side with a laser fan. A CCD video camera connected to a VCR is placed above the window. Particle injection is then started very carefully, one particle at a time. When one particle is present in the sheath, the video recording clearly shows that the particle is spinning around. The non-spherical geometry causes an anisotropy in the light scattering pattern of the single particle: this allows for the visualization of the particle spin. Next, a second, much bigger, particle is injected. The video now clearly shows that both particles are spinning, and the smaller particle is describing a precession movement around the bigger particle: it orbits the bigger particle very slowly. The radius of the orbit of the smaller particle and its angular orbiting velocity strongly depend on the discharge conditions. When more of the smaller particles are injected, the cloud displays collective expansion and contraction, as well as more complicated oscillation patterns. If the amount of injected particles is large enough, the particle cloud condenses in a Coulomb crystal. At that time, the spinning stops: the particles remain stable. The anisotropy of the scattering intensity of all particles is aligned in one direction, perpendicular to the laser beam. It is suspected that this is caused by a combination of mutual attraction of the heads and tails of the particles which show a charge distribution caused by an induced dipole moment on the one hand and the laser radiation pressure on the other hand. The results which will be shown are very recent, and the purpose of the presentation is to invoke discussion on the physical phenomena behind the observations.

Modeling Gas-Phase Nucleation in Inductively-Coupled Silane-Oxygen Plasmas

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Inductively-coupled plasmas (ICP's) are widely used as a high density plasma (HDP) source for various thin film deposition and etching processes during integrated circuit fabrication. An undesirable byproduct of many of these processes is the gas-phase nucleation of contaminant particles. In this work, we present a fundamental kinetic approach to modeling gas-phase nucleation of silicon oxide particles in inductively-coupled silane-oxygen plasmas.

A detailed chemical kinetics mechanism was developed to predict clustering during HDP chemical vapor deposition of SiO_2 films from silane-oxygen-argon mixtures. Our mechanism is based on the recent neutral chemistry mechanism for clustering during low-pressure silane oxidation by Suh, Zachariah and Girshick[1]. We extended that mechanism to include the following classes of reactions that are expected to be important in HDP environments: (1) electron impact reactions with neutral and charged clusters of SiO, SiO_2, SiH_2O and HSiOOH; (2) mutual neutralization of charged clusters; and (3) clustering reactions between neutral and charged species. Thermochemical properties of charged clusters were obtained by utilizing *ab initio* data for the corresponding neutral clusters together with estimates of their electron affinities and ionization potentials. Rate parameters were obtained either from the literature where available or from simple scaling laws[2] for analogous reactions.

An ICP reactor was modeled by constructing a set of one-dimensional conservation equations for mass, momentum and energy within a multi-component two-temperature framework. A Maxwellian distribution for electron energy was assumed. The space-charge-induced electric field was obtained by assuming ambipolarity, while the external electric field for inductive heating of electrons was modeled by using the standard skin effect law. A very thin sheath was assumed by imposing a discontinuity of plasma potential at the boundary (the film deposition surface). The positive ion flux was constrained by the Bohm criterion, while the flux of negative ions was set equal to zero at the boundary. The electron density was obtained by satisfying quasineutrality in the bulk plasma.

The clustering mechanism was self-consistently coupled to the reactor model, and simulations were conducted for a variety of discharge parameters. Spatial distribution of species concentrations, electron temperature, and plasma potential were predicted. The effects of discharge parameters were examined, and the main processes contributing to cluster formation were assessed.

The methodologies and results presented in this study will provide a tool that will allow proper selection of reactor designs and operating conditions that optimize film growth rates and properties while minimizing particle contamination in the microelectronics manufacturing process.

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In-situ detection of dust-particles of less than 5 nm in diameter grown in an argon-silane plasma.

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In the last few years much work has focussed on the impedance of the discharge in order to measure the electrical parameters of the plasma[1]. In this paper we present a method also based on the analysis of the radio-frequency (RF) discharge impedance which enables detection of the particle occurrence when their size is about 2 nm. The discharges considered here are non-symmetrical and capacitive like and present two or more sheaths where the relation between the RF voltage and the RF current is non-linear. This non-linearity induces the appearance of harmonics in the discharge current which can give significant information about the electron and ion dynamics[2].

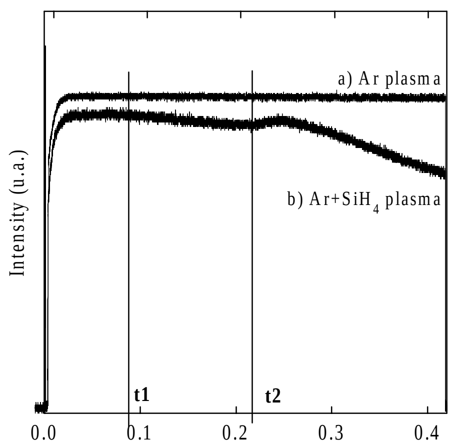

Fig. 1: Time evolution of the third harmonic for a pure argon and a dust-forming plasmas.

Figure 1 shows the time evolution of the amplitudes of the third harmonic for a pure argon plasma and for an Ar-SiH_4 dust-forming plasma. For the pristine situation the intensity of this harmonic remains constant while for the dusty situation the amplitude is strongly affected by the appearance of the particles in the discharge. From this figure one can clearly define two times t1 and t2 which correspond first to the beginning of the influence of the dust-particles on the plasma properties and secondly to the start of the coalescence phenomenon. It is important to point out here that the modifications observed at t1 are due to 2-3 nm in diameter particles.

This diagnostics seems to give a very clear view of the different particle formation phases. All the results we deduced from the time evolution of the amplitudes of the first and third harmonics are in a good agreement with the previous results obtained by means of other diagnostics[3]. Moreover this method is non intrusive as based on the use of a current probe which does not disturb the discharge. Its calibration will certainly allow the determination of the microscopic parameters of the plasma.

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MODELING OF PARTICLE GENERATION AND GROWTH IN SILANE LOW-PRESSURE PLASMAS

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Silane plasmas used for the deposition of amorphous hydrogenated silicon films in the manufacture of solar cells are prone to gas phase nucleation of particles. Up until now, conditions leading to particle generation in the plasma were avoided since it was believed that the particles would increase the defect density in the film. However, in a recent surprising development[1] it was found that conditions leading to formation of extremely small particles (diameters in the 1-2 nm range) actually enhance the film stability against light induced defect creation (Staebler-Wronski effect). We have developed a model for particle formation and growth in silane plasmas. At present, a comprehensive chemical clustering model[2] for particle nucleation in the plasma has been coupled to a model describing particle growth via coagulation and surface growth. Figure 1 shows the different processes that are included in the model. In Figure 2, we show the results of the evolution of the particle distribution function for pure silane at 100 mTorr and 500 K, and a positive ion density of 3.2×10^9 cm^{-3}. Preliminary results from our simulations for particle growth will be presented for a broad range of plasma conditions. This work is supported by NSF grant ECS-9731568.

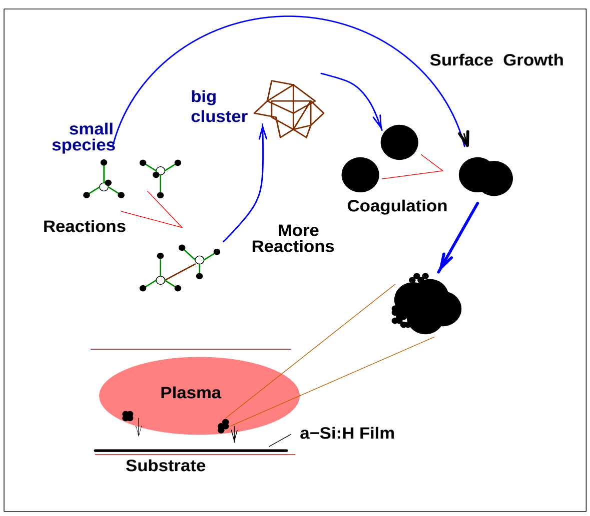

Fig.1. Particle formation and growth in silane plasmas: nucleation due to chemical clustering and particle growth due to coagulation and surface growth.

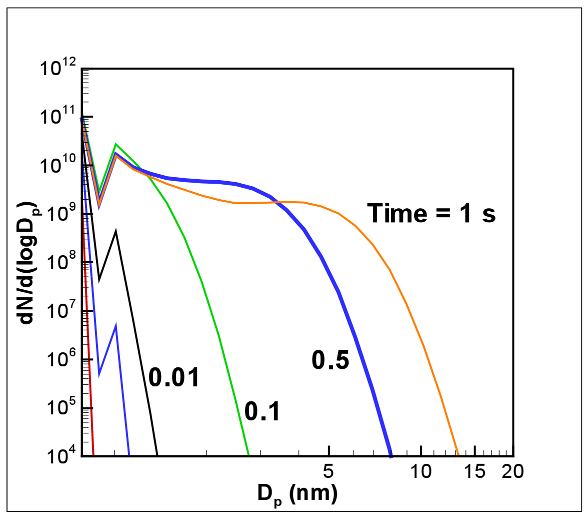

Fig.2. Particle distribution function as a function of time. Gas pressure and temperature: 100 mTorr and 500K. Positive ion density: 3.2×10^9 cm^{-3}.

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Diamond Dust in a Plasma

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We have established a new method for producing diamond particles on a substrate in a low-pressure methane-hydrogen plasma. This method is provided by active electron-temperature control in low-pressure discharge plasmas. The diamond particles produced have been confirmed by the Raman spectroscopy to have an excellent crystal structure in comparison with those produced by other methods.

This method of diamond production has suggested an experiment on levitation of diamond particles in a plasma. The particles of 1-10 micron in size, which have various shapes of polyhedron with strong edges on their surfaces, are injected into a low-pressure Ar discharge plasma. The particles injected are observed to levitate in form of diamond-particle cloud, although each particle shows a violent motion on a horizontal plane. This “diamond dust” shows many interesting features different from usual fine-particle clouds levitated in low-pressure plasmas.

Measurements have also been made on diamond dust levitated in a low-pressure methane-hydrogen plasma in order to find a change of diamond particles levitated under reactive condition. Preliminary results show that the particles are not only recognized to grow but also some new particles are produced in this reactive plasma. Details of the phenomena will be clarified in the near future.

Effect of Trapped Ions on Shielding Around a Grain and Ion Flux to Grain*

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The most basic problems in dusty plasma physics are the determination of the charge of a single grain immersed in plasma, the ion flux to the grain, and the shielding around the grain. Beginning with Langmuir[1], theoretical analyses of these problems have generally been based on the assumption that collisions can be neglected, since the mean free path λ_{mfp} is typically long compared to shielding length scales, i.e. the Debye length λ_D. However, investigators beginning with Bernstein and Rabinowitz[2] have speculated that negative-energy trapped ions, created by occasional collisions, might be important. We have performed an analytic calculation of the density of both trapped and untrapped ions, self-consistent with a calculation of the potential, for a stationary grain in non-flowing plasma.[3] We show that under typical conditions for dust grains immersed in a discharge plasma, trapped ions dominate the shielding cloud in steady state, even in the limit $\lambda_{mfp} >> \lambda_D$. In fact, in the limit $\lambda_{mfp} \rightarrow \infty$ the steady state density of trapped ions is independent of λ_{mfp}, as pointed out by Goree.[4] The problem depends mainly on two dimensionless parameters, T_n/T_e and a/λ_D, where T_n is the neutral molecule temperature, T_e is the electron temperature, and a is the grain radius. The trapped ion density near the grain can be many times larger than the untrapped density in the regime $a^2/\lambda_D^2 << T_n/T_e << 1$, as shown in Fig. 1. As a result, the shielded potential is quite different from the Debye form or the results of orbital motion limited (OML) theory, as shown in Fig. 2. Collisions also substantially increase the ion current to the grain, by an amount which is proportional to the collision frequency. As a result, the negative floating potential of the grain, and the charge on the grain, can be suppressed by a factor as large as two to three. These analytic results appear to be in agreement with a recent Monte Carlo calculation by Zobnin, et al.[5]

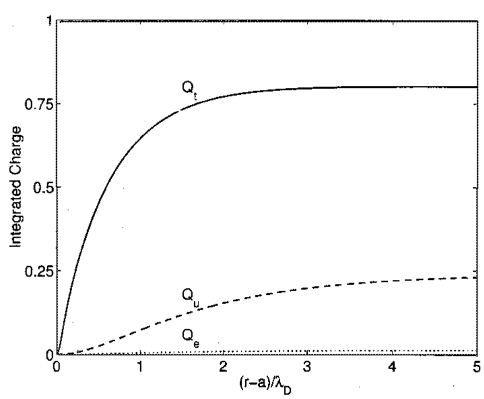

Fig. 1. Charge enclosed within radius r, scaled to grain charge. Q_t: trapped ions. Q_u: untrapped ions (deviation from ambient). Q_e: electrons (deviation from ambient).

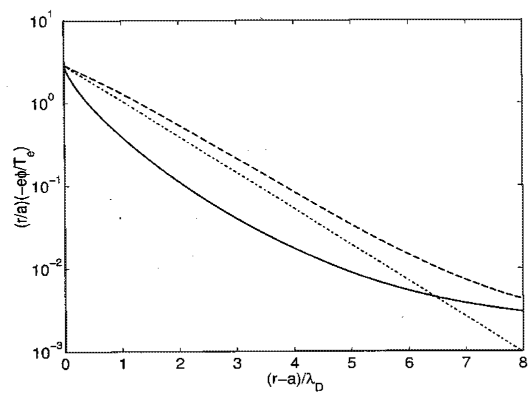

Fig. 2. $(r/a)[-e\phi(r)/T_e]$, where $\phi(r)$ is the shielded potential. Solid curve: present calculation. Dotted line: Debye-shielded Coulomb. Dashed curve: OML theory.

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On the charging of a dust particle: theory and some experimental considerations

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Theory. The traditional method used to determine the charge acquired by a dust particle in a plasma is by means of the Orbital Motion Limited (OML) theory. This theory has its origins in probe theory for the case of an infinitely large sheath. This method, however, is incomplete in that the potential distribution around the particle is not determined. It has been pointed out, however, that the potential distribution must satisfy a certain criterion if the OML theory is to be valid, namely $V/V_p>(r_p/r)^2$ [1]. Hence it is imperative to solve Poisson's equation to determine the potential distribution. It has been shown recently that the OML theory is in fact never valid for Maxwellian plasmas, at least when T_i is less than or equal to T_e [2].

Calculations have now been made for the cases of zero and finite ion temperature. In the first case it has been shown that the floating potential tends to zero for very small particles [3,4]. The calculations for the complete orbital motion theory have now also been completed [5,6]. It turns out that for small values of the particle radius, compared with the Debye distance, and for small values of the ratio T_i/T_e, the results obtained using the OML are not greatly in error. This is because the number of ions having an *absorption radius* [1] is very small. In general the floating potential is larger in magnitude than that predicted by the OML theory, approaching that given by "thin sheath theory" as the particle size increases.

Some experimental considerations. The method used to determine the charge acquired by a dust particle is to determine the period of oscillation around the equilibrium position in the sheath, most "dusty plasma" experiments being carried out not in the plasma but in the space charge sheath situated below the plasma. The particular method employed in Oxford is to observe damped oscillations [7] rather than the forced oscillations employed by other groups. It has often been assumed that the electric field in the sheath varies in a linear fashion, it has now been demonstrated that this is very nearly true irrespective of the sheath model employed [8].

Another method of determining the charge [8] is to use the fact that the gravitational force is balanced by the electric force on the particle, ignoring the small ion drag. It is somewhat surprising that this method has not been used before, to the best of our knowledge.

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An experimental technique to accomplish very large plasma-crystals with up to 10 million particles

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A new experimental arrangement gives the possibility to assemble a complex (dusty) plasma volume of 2.5x4x4cm in a symmetric RF-excited plasma chamber. A volume of this size allows the study crystal structures of a very large number (10 to 7th) of particles, the production of plasma crystals in the charge neutral region of a RF-discharge, the visualization of melting of a 3D body in a sideview and the study of wave propagation in stratified and discontinuous systems e.g. across the boundary between zones of different particle sizes. Finally equation of state theories can be studied experimentally.

Formation and confinement of dust clouds in the Auburn Dusty Plasma Experiment

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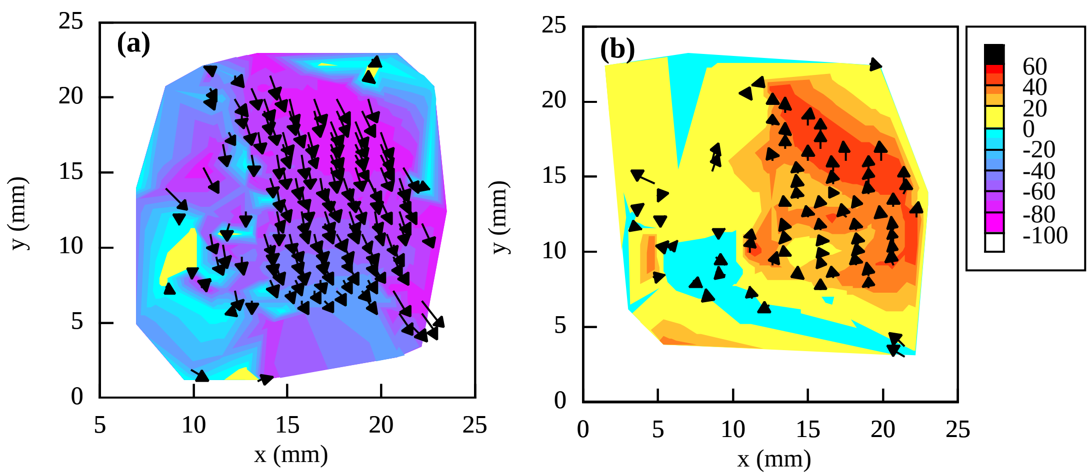
An experimental study of the formation of dust clouds is performed using the Auburn Dusty Plasma Experiment. In these studies, clouds of 3 μm diameter silica microparticles are suspended in argon dc glow discharge plasmas. The microparticles in these clouds are either in a fluid-like state or strongly coupled, but non-crystalline state.[1] The plasma is generated using both a biased anode (V_a ~ 190 to 240 V) and a biased cathode (V_c ~ -90 V to -150 V). Through the use of the particle image velocimetry (PIV) technique,[2] the spatial and temporal behavior of the dust particles can be determined.

In these experiments, the bias voltage on the cathode is momentarily varied (typically for 30 to 100 ms) using a programmed square wave pulse. The application of this pulse to the cathode causes a loss of confinement of the dust particles as shown by the downward (i.e., in the direction of gravity) particle motion in Fig. (a). Once the bias voltage on the cathode is restored, the particles begin to re-form the dust cloud. This is indicated by the upward particle motion in Fig. (b). The time difference between Figs. (a) and (b) is 120 msec and particle velocities are indicated in units of mm/s. From the trajectories of the microparticles during this formation process, it is possible to estimate of the electric potential in the vicinity of the dust cloud.[3]

This presentation will discuss the experimental configuration of the Auburn Dusty Plasma Experiment used to make these measurements. The presentation will also present measurements of the time evolution of the potential profile near the dust cloud based upon this use of the microparticles as floating probes.



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[1] E. Thomas, Jr. and M. Watson, Phys. Plasmas, **6**, 4111 (1999).
[2] E. Thomas, Jr., Phys. Plasmas, **6**, 2672 (1999).
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Modeling of Particle Charging in Homogeneous Dusty Plasma

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The phenomenon of dusty plasma creates a physical situation in which nanoscale (dust) particles are formed from molecular species and acquire charge by interacting with the plasma particles (electrons and ions). These stochastic interactions and discrete nature of plasma particles distribution and charge result in the stochastic nature of dust particles charging. Modeling of the charging mechanism in the framework of kinetic or probability distribution function (pdf) approach requires tackling a closure problem (arising as a result of fluctuation-fluctuation interactions) similar to the well known turbulence closure problem. We use Direct Interaction Approximation (DIA) [1] to solve the closure problem and obtain an approximate equation governing the pdf $p(q,t)$ of dust particles charge q at time t in homogeneous dusty plasma.

Our analysis [2] starts from the equation for phase space density $P(q,t)$ written as [3]:

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial q}I-\frac{\partial^2}{\partial q^2}Q\right]P(q,t)=0;\quad I=\sum_\sigma\int e_\sigma\gamma_\sigma v_\sigma f_\sigma d\mathbf{v}_\sigma;\ Q=\frac{1}{2}\sum_\sigma\int e_\sigma^2\gamma_\sigma v_\sigma f_\sigma d\mathbf{v}_\sigma. \tag{1}$$

Here, subscript $\sigma=\{i,e\}$ represents properties for ions (i) and electrons (e), $f_\sigma(\mathbf{r},\mathbf{v}_\sigma,t)$ represents the phase space density (stochastic in nature) for plasma particles, and $\mathbf{r}$ and $\mathbf{v}_\sigma$ are position and velocity of plasma particles, respectively, $v_\sigma=|\mathbf{v}_\sigma|$ and γ_σ is the cross section for charging collisions and is determined by the Orbital Motion Limited approach.

The equation for pdf can now be obtained by taking the ensemble average (denoted by $< >$ and overline) of (1) over a large number of realizations and normalizing it by the total number of dust particles n_0. We define

$$P(q,t)=n_0p(q,t)+\tilde{P}(q,t),\ n_0p=<P>,\ <\tilde{P}>=0;\quad f_\sigma=\overline{f}_\sigma+\tilde{f}_\sigma,\ \overline{f}_\sigma=<f_\sigma>; \tag{2}$$

$$I=\overline{I}+\tilde{I};\ \overline{I}=<I>;\quad Q=\overline{Q}+\tilde{Q},\ \overline{Q}=<Q>;\quad <\tilde{I}>=<\tilde{Q}>=<\tilde{f}_\sigma>=0, \tag{3}$$

and then the ensemble average of (1) is written as

$$\frac{\partial}{\partial t}p(q,t)+\frac{\partial}{\partial q}[\overline{I}\,p(q,t)]-\frac{\partial^2}{\partial q^2}[\overline{Q}\,p(q,t)]=-\frac{1}{n_0}\frac{\partial}{\partial q}[<\tilde{I}P(q,t)>]+\frac{1}{n_0}\frac{\partial^2}{\partial q^2}[<\tilde{Q}P(q,t)>], \tag{4}$$

carrying unknown correlations $<\tilde{I}P>$ and $<\tilde{Q}P>$ which pose a closure problem. Application of DIA gives expressions for the correlations and under the condition when fluctuations change rapidly in time, an approximate equation for $p(q,t)$ is written as [2]:

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial q}\overline{I}-\frac{\partial^2}{\partial q^2}(\overline{Q}+D_1)+2\frac{\partial^3}{\partial q^3}D_2-\frac{\partial^4}{\partial q^4}D_3\right]p(q,t)=0,\quad \text{where} \tag{5}$$

$$D_1(q,t)=\int_{t_0}^{t}\overline{\tilde{I}(q,t)\tilde{I}(q,s)}\,ds,\quad D_2(q,t)=\int_{t_0}^{t}\overline{\tilde{I}(q,t)\tilde{Q}(q,s)}\,ds,\quad D_3(q,t)=\int_{t_0}^{t}\overline{\tilde{Q}(q,t)\tilde{Q}(q,s)}\,ds$$

and initial condition for p is known at time $t=t_0$.

Macroscopic equations are then obtained from (5) for $\overline{q}(t)=\int q\overline{f}(q,t)\,dq;\ S_n=\int(q-\overline{q})^n\overline{f}(q,t)\,dq$, where $\overline{q}$ is the average value of charge on the particles and S_n represents the nth moment of fluctuations in q over its mean value $\overline{q}$.

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